

# Proposal for an experimental test of the many-worlds interpretation of quantum mechanics

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## Abstract

The many-worlds interpretation of quantum mechanics predicts the formation of distinct parallel worlds as a result of a quantum mechanical measurement. Communication among these parallel worlds would experimentally rule out alternatives to this interpretation. A procedure for “interworld” exchange of information and energy, using only state of the art quantum optical equipment, is described. A single ion is isolated from its environment in an ion trap. Then a quantum mechanical measurement with two discrete outcomes is performed on another system, resulting in the formation of two parallel worlds. Depending on the outcome of this measurement the ion is excited from only one of the parallel worlds before the ion decoheres through its interaction with the environment. A detection of this excitation in the other parallel world is direct evidence for the many-worlds interpretation. This method could have important practical applications in physics and beyond.

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# 1 Introduction

There has been a renewed intense interest in the quantum mechanical measurement problem recently[1]. The reason for this is a growing dissatisfaction with the orthodox[2] and statistical [3] interpretations which do not allow to derive the properties of the classical reality from the Schrödinger equation even in principle. A further problem is that both interpretations use concepts (“reduction of the state vector” in the former and “conceptual ensemble of similarly prepared systems” in the latter) that are described only by words and not mathematically, so their meaning remains vague. Moreover in the orthodox interpretation the human consciousness has to play a special role in physics (in the words of Bohr the purpose of physics is “... not to disclose the real essence of phenomena but only to track down ... relations between the manifold aspects of experience” [4]), a notion that does not go easy with the majority of physicists.

For simplicity I will consider in this paper only the simple case of measurements with two discrete results. A generalization to the case of more than two outcomes is straightforward. According to the classical book on quantum measurements in the orthodox interpretation by von Neumann[5], a quantum mechanical measurement consists of a “process 1” or “collapse of the wavefunction”: a coherent wave function  $\psi$  (which contains a complete description of the quantum mechanical system and of the measurement apparatus), is suddenly converted to a statistical mixture of  $\psi_1$  which describes one possible outcome of the measurement, and  $\psi_2$  which describes the other outcome. This state reduction is not derived from the Schrödinger equation (called “process 2” by von Neumann) but introduced ad hoc to explain the observed facts.

An important progress during the last decade was the realization that “decoherence” plays a decisive role in a quantum mechanical measurement[6]. Decoherence explains “process 1” as a loss of phase relations in the wavefunction  $\psi$  of the measuring apparatus while it interacts with the quantum system. This loss is a continuous process and can be quantitatively calculated in a variety of situations[6] without going beyond the Schrödinger equation. Process 1 needs a finite amount of time in this view because of its continuous nature, the so called “decoherence time”  $\Delta t_{dec}$ , which is very short in most “usual” measurement situations (i.e. the measurement apparatus is macroscopic and interacts strongly with the quantum system). The sudden reduction envisioned by von Neumann is a very good approximation which suffices for a description of practical situations up to now. A complete statistical mixture is never reached, but if one takes into account that macroscopical measurement apparati always interact with a large environment, the assumption of a statistical mixture becomes extremely good and can explain all observational facts.

There remains one question (quoted here directly from Omnès[7]): after decoherence has taken place... “why or how does it happen that an apparatus shows up unique and precise data (in our case: either  $\psi_1$  or  $\psi_2$  is actually observed) whereas the theory seems only to envision all possibilities on the same footing?”. This necessity of some mechanism in

addition to “process 1” (sometimes called “objectification” or “actualization”) was already recognized by von Neumann; he calls the measurement apparatus “II” and the apparatus “with the actual observer” “III”. He only states that the interaction between “II” and “III” “remains outside the calculation” [5](chapt.VI.1). Proposals to answer Omnès question can be grouped in three categories:

- there are so called “hidden variables”, arising from some extension to the Schrödinger equation which causes actualization (not necessarily in a deterministic way) [8]. A violation of the Bell inequalities in EPR type experiments has been shown with great precision in a variety of set ups recently [9]. If one does not want to take recourse to contrived conspiracies (see Ref.[10] how to exclude even these), any hidden variable theory has to introduce non-local interactions as a consequence; this would require a revision of many physical concepts.
- the question is declared “meaningless”; “actualization” occurs without any *mechanism*. e.g. Hartle states [11] “We do not see it (i.e. actualization) as a “problem” for quantum mechanics.” This standpoint is logically consistent and leads to the so called “logical” [1] and “many histories” [12] interpretation of quantum mechanics. These (quite similar) interpretations include decoherence in their description of nature and thus go far beyond the orthodox interpretation. Actualization is obviously crucial for our perception of nature, but it is not considered to be a part of physics in this view. Therefore these interpretations (like the orthodox interpretation) have to renounce the existence of an “independent reality”, a physical universe which exists independent of our consciousness, Omnès states: “physics is not a complete explanation of reality...theory ceases to be identical with reality at their ultimate encounter...” [1].
- a very radical and elegant answer was given by Everett [13]: after decoherence has taken place, the orthogonal states  $\psi_1$  and  $\psi_2$  (each also describing an independent “split” observer) continue to evolve according to the Schrödinger equation and have “equal rights”. In this view “actualization” is explained as an illusion in the brain of a human observer: after a few decoherence times, his weak senses and crude measuring devices are unable to detect the increasingly weak influences of the other “outcome”. He therefore calls the one outcome he can see “the world”. The same happens with the other outcome. For this reason DeWitt termed the name “many-worlds interpretation” (MWI) for this view of nature [14]. I will use the word “universe” to indicate space time together with all “worlds” existing in it. I call the two outcomes of a measurement “parallel worlds” below, because they exist in the same Minkowskian space time. The worlds which form as a result of a measurement with a finite number of discrete outcomes are usually called “branches”. In Hilbert space the parallel worlds are orthogonal of course. Together with decoherence (a concept still unknown when Everett wrote his thesis) this idea leads to a deterministic view of the universe in which the human mind plays no special role outside physics [15].

Section 2 contains a general discussion of the method for an experiment to test Everett’s interpretation. Section 3 provides a detailed analysis of a decoherence process which is of critical importance for the experiment. A reader mainly interested in the practical re-

alization of the experiment can skip this somewhat technical part and proceed directly to section 4. Here a concrete example for a possible technical setup is given. In the conclusion (section 5) the predictions of the various interpretations of quantum mechanics for the outcome of the proposed experiment are compared, and the potential practical importance of a result confirming the MWI is stressed.

## 2 Proposal of an experiment to test the many-worlds interpretation

The MWI together with decoherence corresponds to the conceptually very simple view that nonrelativistic quantum mechanics can be understood by assuming only the existence of objectively real wavefunctions whose evolution is governed by the usual Schrödinger equation, together with the second quantization conditions of the underlying wave field, without any subjective or non-local elements. It is therefore important to find experimental tests for this interpretation. Independent of what one thinks about the MWI a priori, this is also a very *systematic* way to make experimental progress in the question of the interpretation of quantum mechanics, because in the MWI the predictions for any conceivable experiment are free from philosophical subtleties (which can be a problem in the orthodox interpretation) or free parameters (which often occur in one of the many proposed hidden variable models).

I already mentioned that decoherence only leads to approximate mixtures (though the approximation is extremely good in most situations)[14]. The separation of worlds in the MWI is never quite complete therefore, and there should be small influences from a parallel world even after decoherence, *which must be measurable in principle*. This has been most clearly pointed out by Zeh[16, 17]. In Ref.[16] he discusses the possibility to observe “probability resonances” (later further discussed by Albrecht[18]), which occur at a singular point when the amplitudes of  $\psi_1$  and  $\psi_2$  have exactly the same magnitude. An experiment to test the MWI against the orthodox interpretation along similar lines was proposed by Deutsch [19]. Unfortunately it is still far from practical realization, as it requires a computer which remains in a quantum mechanically coherent state during its operations and in addition possesses artificial intelligence comparable to that of humans.

I will describe an experiment for testing the MWI with state of the art technology. Imagine a human called Silvia which is programmed to perform different actions in dependence on the outcome of a quantum mechanical measurement. For our purposes Silvia might just as well be imagined e.g. as a suitably programmed commercially available computer connected to the experimental equipment via a CAMAC crate instead of as a human. As an example Silvia sends a linearly polarized photon through a linear polarization filter. Let the photon be in a state  $|P\rangle$ , such that the filter axis of complete transmission is at  $45^\circ$  to the linear polarization plane of the photon. She is programmed (decides) to switch on a microwave

emitter if she will measure that the photon passed through the linear-polarization filter into photomultiplier tube and to refrain from doing so if she will find that the photon was absorbed by the filter. If one assumes detectors with 100 % efficiency for simplicity, the probability for either outcome is 50 %. In the MWI there are two independent humans after the measurement was performed and decoherence took place: one which detected a photon and switched on the emitter (called “Silvia1” below) and the other that didn’t (“Silvia2”). Could these humans (Silvia1 and 2) communicate with each other? The standard answer in the MWI is no, because decoherence is so complete after very short time scales that no one of them can influence the world of the other, which is of course necessary for communication.

One could isolate a small part of the original apparatus (before the measurement takes place) so perfectly that it does not immediately participate in the decoherence. It is now possible in principle to change the state of this isolated part *before* it is completely decohered by means of an influence from only one of the two worlds. In this way it could act as a “gateway state” between the parallel worlds. Because it is only partially decohered, it can still be influenced by both worlds (and in turn can influence both worlds), thus making possible communication. For humans an isolation on a time scale of at least seconds would be necessary for real communication. For the current electronic computers a time scale of  $\mu$ secs and for simple macroscopic logic electronic (e.g. in the commercial NIM standard) nsecs would be enough to verify the existence of the parallel world.

This proposition is not realistic if the “gateway state” is macroscopic, because the required isolation would be difficult to achieve technically (see however recent experiments with macroscopic quantum systems e.g. Ref.[20]). Since the late 1970s it has become possible to perform precision experiments on single ions stored for long times in electromagnetic traps[21]. I will show in section 4 that these single ions are isolated from the environment to such a degree that the decoherence timescale is on the order of seconds or longer with existing technical ion-trap equipment. Moreover it is possible to excite these atoms before they are correlated with the environment to such a degree that complete decoherence took place. In our example above Silvia1 switches on the microwave emitter long enough to excite an ion in a trap with a large probability. After that, Silvia2 measures the state of the ion and finds that it is excited with some finite probability, though Silvia verified it was in the ground state before the branching took place. From that Silvia2 infers the existence of Silvia1. In an obvious way Silvia1 and 2 can exchange informations (bit strings of arbitrary length), e.g. by preparing more than one isolated ion. Single ions in traps can act as “gateway states” and communication between parallel worlds is possible.

Let us write down the evolution of the wave function describing the proposed experiment explicitly in several time steps. We write the initial wave function  $|\Psi_{t_0}\rangle$  of our system (the laboratory with all its contents shortly before the experiment begins at time  $t_0$ ) as a direct product of several “subsystems” (in the sense of Zurek [6]). The chosen factoring is somewhat arbitrary, the final results are independent of the choice to a good approximation,

however.

$$(1) \quad |\Psi_{t_0}\rangle = |P\rangle \otimes |\phi_{filter}\rangle \otimes |\phi\rangle \otimes |A\rangle$$

Here  $|P\rangle$  stands for the initial state of the photon which can be represented by the coherent superposition  $\frac{1}{\sqrt{2}}(|P_1\rangle + |P_2\rangle)$  of the two polarization states of the photon (the subindex 1 indicates a polarization plane parallel to the transmission direction of the filter, and 2 at a  $90^\circ$  angle to this direction).  $|\phi_{filter}\rangle$  describes the polarization filter,  $|\phi\rangle$  describes the laboratory including all further experimental equipment, possibly produced microwave fields and Silvia. The isolated ion in its trap is symbolized by  $|A\rangle$ . A commercial linear polarization filter is macroscopic and its Poincaré recurrence time is much larger than any other time scale in the experiment. Therefore it qualifies as “environment” [6] and some time after the photon  $|P\rangle$  has interacted with the filter (at time  $t_1$ ) the two components of  $|P\rangle$  have decohered and we obtain to very good precision two distinct decohered subsystems (“worlds”). Let us call this time, when  $|\phi_{filter}\rangle$  has already decohered but the other subsystems  $|\phi\rangle$  and  $|A\rangle$  did not yet interact with  $|P\rangle$  “ $t_1$ ” (such a time can surely be found, even if it would be only because of the finite  $c$ ). At this time the state of the subsystem “photon and filter” no longer corresponds to any one ray in Hilbert space (it is described by a mixture). Rather the decoherence process has selected two special states. While the exact nature of these states is not yet entirely clear, current research suggest that they are characterized by maximal thermodynamical stability, i.e. they are states with minimal increase in entropy[22]. Let us symbolized these two orthogonal vectors in Hilbert space in the following way:

$$(2) \quad |W_1\rangle = |P_1\phi_{filter1}\rangle$$

$$(3) \quad |W_2\rangle = |P_2\phi_{filter2}\rangle$$

I left out the direct product symbol  $\otimes$  between the symbols to indicate that they are in an entangled state. These functions are very nearly orthogonal to each other and will stay like that forever. However one should not conclude that the process of decoherence is already finished. It is finished only later when all subsystems are decohered. The rest of the laboratory and the ion can still be described by pure states as can the state of the total system at time  $t_1$ :

$$(4) \quad |\Psi_{t_1}\rangle = \frac{1}{\sqrt{2}}(|W_1\rangle + |W_2\rangle) \otimes |\phi\rangle \otimes |A\rangle$$

Just like the polarizer “measured” the two states of the photon  $|P\rangle$  via decoherence, the subsystem  $|\phi\rangle$  (including Silvia) “measures” the state of the polarizer. The resulting decoherence leads to two distinct subsystems:  $|W_1\rangle = |P_1\phi_{filter1}\phi_1\rangle$  (“photon detected world”) and  $|W_2\rangle = |P_2\phi_{filter2}\phi_2\rangle$  (“no photon detected world”). The final state at a time  $t_2$  can be written as:

$$(5) \quad |\Psi_{t_2}\rangle = \frac{1}{\sqrt{2}}(|P_1\phi_{filter1}\phi_1\rangle + |P_2\phi_{filter2}\phi_2\rangle) \otimes |A\rangle$$

The “branches”  $|W_1\rangle$  and  $|W_2\rangle$  are orthogonal to a very high precision, this also guarantees the stability of the records whether the polarized photon was detected in the further evolution of the system. To reach a final state at time  $t_3$  in which also  $|A\rangle$  is decohered into two components (see below and section 3 for a more detailed discussion of this decoherence process), the ion has to interact with the rest of our system. It is possible to excite the ion during the decoherence process, i.e. the interaction during the time interval  $\Delta t_{dec}=t_3-t_2$  can excite A. When I fine tune the technical set up I can make sure that the time interval  $\Delta t_{exc}$  necessary to excite  $|A\rangle$  to  $|A^*\rangle$  is much smaller than  $\Delta t_{dec}$ . These two time scales have no direct relation to each other. In this case we have for the final state:

$$(6) \quad |\Psi_{t_3}\rangle = \frac{1}{\sqrt{2}}(|P_1\phi_{filter1}\phi_1A_1^*\rangle + |P_2\phi_{filter2}\phi_2A_2^*\rangle)$$

It is of course also possible not to excite  $|A\rangle$  in the course of decoherence. The possibility of this choice allows for communication. The excitation of an internal degree of freedom of a subsystem does not necessarily lead to decoherence as the reader might think at first. A counter example are *Welcher Weg* detectors[23], in which atoms can be excited in micro-masers without momentum transfer and necessary loss of quantum coherence.

Let us discuss in more detail what happens when  $|A\rangle$  is excited from only one world. Immediately after the excitation, at time  $t_2+\Delta t_{exc}$  ( $\Delta t_{exc} \ll \Delta t_{dec}$ ), only a part of the phase space in which the ion resides is excited. It is the part corresponding to the one macroscopic world  $|W_1\rangle$  exciting the ion (macroscopic states are very well localized in phase space[25]). After unitary evolution of  $|A\rangle$  for a short time interval of the order of  $\Delta t_{mix} = d_{coh}m/\Delta p \simeq d_{coh}dm/h$ , the excited part of phase space begins to overlap with the unexcited one and it is no longer possible to treat their temporal evolution independently. Here  $d_{coh}$  is the coherence length of the system in the branch exciting the ion, which is extremely small for macroscopic objects[25],  $m$  is the mass of the ion and  $\Delta p$  is the momentum uncertainty of a region in phase space with extension  $d_{coh}$ . The momentum uncertainty  $\Delta p$  is approximately given as  $h/d$  where  $d$  is the spatial extension of the trap. A time scale analogous to  $\Delta t_{mix}$  (“duration of reduction”) in a somewhat different situation was introduced by Dicke[24].  $\Delta t_{mix}$  can be shown to be negligibly small for all experimental purposes (very roughly  $O(10^{-15}$  sec) for typical trap sizes ( $\mu m$ ) and decoherence lengths as quoted by Tegmark[25]). Because of the mentioned overlap a measurement of the excitation of  $|A\rangle$  from the other world  $|W_2\rangle$ , which measures another part of phase space than a measurement from  $|W_1\rangle$ , also finds the ion in an excited state. Only after complete decoherence of  $|A\rangle$  the parts of phase space seen by  $|W_1\rangle$  and  $|W_2\rangle$  have an independent temporal evolution.

### 3 Determination of the decoherence timescale of the single ion

I now quantitatively calculate the time scale  $\Delta t_{dec}$  if the decoherence of the ion wavefunction  $|A\rangle$  into  $|A_{1,2}\rangle$  as defined in the previous section. For this I will analyze the transition from

eq.(5) to eq.(6) in greater detail than before. This analysis is independent of whether the ion is excited between  $t_2$  and  $t_3$  or not. I will use the “dilute gas” approximation developed by Harris and Stodolsky [26, 27]. The interaction of systems is treated in terms of a series of distinct collisions between the ion in the trap and particles from the rest of the system. The correctness of this simplification in the case of weak coupling has been verified with a full second quantized calculation by Raffelt, Sigl and Stodolsky[28]. The chirality states  $|\pm\rangle$  of Harris and Stodolsky[26] are analogous to our macroscopic states  $|W_{1,2}\rangle$  of the previous paragraph, and their “medium” is the ion in the trap in our case. Parallels between the chirality and macroscopic states were already pointed out by Joos and Zeh[29]. It seems strange at first sight that a single ion in a given “simple” state plays the role of the “medium”. With “simple” I mean that the state of the ion in its trap has only few degrees of freedom which are completely determined e.g. by a harmonic oscillator wavefunctions, whereas a “medium” typically has a very large number of degrees of freedom and is thus able to exert random influences on a system. Take into account however that in quantum field theory the wave field always has an infinite number of degrees of freedom[30]. In the MWI it is this field which represents all systems and the “simplicity” of the state  $|A\rangle$  of the ion before decoherence at time  $t_0$  exists *only relative* to the subsystem  $S_1=(|P_1\rangle + |P_2\rangle) \otimes |\phi_{filter}\rangle \otimes |\phi\rangle$  in eq.(1) (Everett called the MWI “relative-state interpretation” [13]). If this subsystem decohered into two orthogonal states  $|W_{1,2}\rangle$  at time  $t_2$  the ion  $|A\rangle$  can no longer be in a “simple” state relative to both of them, and additional degrees of freedom of the wave function  $|A\rangle$  become dynamically important. After interaction of  $|A\rangle$  with the environment, at time  $t_3$  there will be two orthogonal components  $|A_{1,2}\rangle$ . Each one has an overall centre of mass wavefunction described e.g. by a “simple” harmonic oscillator state relative to one of the worlds  $|W_{1,2}\rangle$ . It is wrong to conclude from that that they are identical, however:  $|A_1\rangle$  and  $|A_2\rangle$  are different for the same reason that the “copies” produced by branching from a given macroscopic object are not identical: their “fine structure” in phase space is different.

It is clear that our treatment is a gross simplification of the real world. An exact treatment has been possible only for idealized models of the environment, e.g.: toy systems with few particles [18], ensembles of noninteracting harmonic oscillators[31] and scalar fields[32]. For the gravitational field an exact treatment is not possible even in principle at the moment, because we lack a quantum theory of gravity. It has been shown experimentally though that gravitational fields decohere if the MWI is correct[33]. The purpose of this paper is not to improve on the treatment of the very difficult theoretical problem of decoherence, but to suggest a new experimental approach on the quantum mechanical measurement problem. Our treatment gives roughly the correct order of magnitude for the decoherence time scale. Let us now define the relative states in the sense of Everett[13] of  $|A\rangle$  with respect to  $|W_1\rangle$  and  $|W_2\rangle$  at time  $t_2$  as  $|A_1\rangle = \frac{1}{\sqrt{2}}|A\rangle$  and  $|A_2\rangle = \frac{1}{\sqrt{2}}|A\rangle$ , respectively. At time  $t_2$   $|A_1\rangle$  and  $|A_2\rangle$  are still the same or “parallel” in Hilbert space[27]. We also have  $|A\rangle = \frac{1}{\sqrt{2}}(|A_1\rangle + |A_2\rangle)$  a decomposition which is always possible for a pure state according to the superposition

principle. The total wavefunction at time  $t_2$  can then be written as:

$$(7) \quad |\Psi_{t_2}\rangle = |A_1\rangle|W_1\rangle + |A_2\rangle|W_2\rangle$$

This equation is analogous to equation (3) in Ref.[27]. Further following Harris and Stodolsky[26] we now write this wavefunction in the form of a density matrix in a basis of the Hilbert space spanned by  $|W_{1,2}\rangle$  to represent the role of the phases in a better way:

$$(8) \quad \rho(\Psi_{t_2}) = \begin{pmatrix} \langle A_1|A_1\rangle & \langle A_1|A_2\rangle \\ \langle A_2|A_1\rangle & \langle A_2|A_2\rangle \end{pmatrix}$$

In the initial state  $\Psi_{t_2}$  the ion and its environment are uncorrelated and all elements of this matrix have the value 1/2 in our case. In our approximation decoherence now leads to an exponential damping of the off-diagonal elements of this density matrix, while the diagonal elements remain unaffected. At time  $t_3$  the matrix is given to a very good approximation by 1/2 the identity matrix. The decoherence time scale in the transition from  $\Psi_{t_2}$  to  $\Psi_{t_3}$  is then given as the inverse of the exponential damping time constant. If there was no internal excitation during the process of decoherence,  $|A_1\rangle$  and  $|A_2\rangle$  are identical yet distinguishable in the classical sense (i.e. by way of their structure in phase space) at time  $t_3$ .

I approximate the temporal evolution of the off-diagonal elements of  $\rho$  as an effect of repeated scatterings of particles from  $|W_1\rangle$  and  $|W_2\rangle$ [26]. If the particles in  $|W_{1,2}\rangle$  are atoms (e.g. rest-gas atoms, see below section 4) their de Broglie wavelength ( $< 0.1 \text{ \AA}$  at room temperature) is much smaller than the typical spatial extension of the wavefunction  $|A\rangle$  of the ion in the trap (typically  $0.1\text{-}1 \text{ }\mu\text{m}$  in current technical setups[34]). It is then a good approximation for the treatment of the scattering to assume that the initial state of the ion is approximated by a plane wave front, and that the elastically scattered wave of the trapped ion is approximated by a radially outgoing wave front. I will always use this approximation in the following even in cases where it is less well justified because the wavelength of the scattering particles in  $|W_{1,2}\rangle$  is equal to or larger than the spatial extension of  $|A\rangle$  (e.g. for microwave photons scattering on the ion). In this case the decoherence time scale will be *larger* than my estimate (the scattering is less “effective”). To demonstrate that the decoherence timescale can be large enough to allow interworld communication, my approach is sufficient. Also we will see below in section 4 that in our situation the most effective mechanism for decoherence is elastic scattering with rest gas atoms, for which my assumption holds well.

The diagonal element  $\langle A_1|A_2\rangle$  has to be multiplied by a damping factor  $D$  for each scattering of the ion with a particle of  $|W_{1,2}\rangle$  as a target. If  $|A^S\rangle$  is the wavefunction of the ion after scattering one can write:

$$(9) \quad \langle A_1^S|A_2^S\rangle = D\langle A_1|A_2\rangle$$

The damping factor after  $n$  collisions is given as:

$$(10) \quad D_n = D^n.$$

In the special case of elastic and isotropic scattering and integrating over time one has for the final state after one scattering:

$$(11) \quad A_1^S = o(e^{ikz} + f \cdot e^{ikr}/r)$$

$$(12) \quad A_2^S = o(e^{ikz} + f \cdot e^{(ikr+\Delta\varphi)}/r)$$

where  $k$  is the wave number and  $z$  the direction of relative motion between the particle and the trapped ion.  $f$  is the scattering amplitude and  $r$  the radial distance from the ion.  $\Delta\varphi$  is a relative phase angle which takes random values over repeated scatterings because  $|W_1\rangle$  and  $|W_1\rangle$  are not in phase. The normalization factor  $o$  is given by:

$$(13) \quad o = \frac{1}{\sqrt{1 + f^2/r^2}}$$

Inserting eqs.(11,12,13) into eq.(9) and integrating over the spatial volume one obtains:

$$(14) \quad D = o^2 = \frac{1}{1 + f^2/r^2} \simeq 1 - f^2/r^2$$

The neglect of higher order terms is justified in the dilute gas approximation. For  $n$  consecutive scatterings one gets:

$$(15) \quad D_n \simeq (1 - f^2/(r^2))^n \simeq \exp(-f^2 n/(r^2))$$

Let us set  $f^2 = \sigma/(4\pi)$ , where  $\sigma$  is the total elastic cross section, and  $n = 4\pi r^2 \phi t$ , where  $\phi$  is number of particles per unit area and time on which the ion scatters and  $t$  the time span over which interactions between  $|A\rangle$  and  $|W_{1,2}\rangle$  takes place. The time evolution of the diagonal elements of the ion-environment density function is then obtained as:

$$(16) \quad D_t \simeq \exp(-\sigma \phi t)$$

The decoherence time is then defined as:

$$(17) \quad \Delta t_{dec} = 1/(\sigma \phi)$$

This result for the decoherence time agrees with a different and more general calculation by Tegmark[25] for the special case of a system that is spatially much larger than the effective wavelength of the scattering particles. It was exactly this case that I assumed above. Note that Tegmark calls “coherence time” what I call “decoherence time”.

## 4 Practical realization of communication between parallel-worlds

I will show that it is technically possible to realize a system which approximates the situation outlined in section 2. and which has macroscopic decoherence timescales. For my discussion I will assume the setup which Itano et al.[34] used for a measurement of quantum

projection noise. This is not in order to suggest that this is an optimal setup for inter-world communication; I only wanted to show that the technical capabilities to test the MWI exist in one concrete case.

Itano et al.[34] trap single ions in radio frequency and Penning traps. The ion (I consider  $^{199}\text{Hg}^+$ ) can be stored for hours in a vacuum of about  $10^{-9}$  atmospheres. They observe transitions between the  $6s^2S_{1/2}$   $F=0$  and  $F=1$  hyperfine structure levels by applying rf fields of well-controlled frequency, amplitude and duration. The transition is in the microwave region (40.5 GHz). UV Lasers operated at 194 nm are used to cool the ion, prepare its state and to measure whether the ion is in  $F=0$  or  $F=1$  state after an application of microwaves. In our example Silvia traps an ion and prepares it in the ground state. If Silvia1 now detects a photon after the polarization filter she applies the rf field resonant with the  $F=0 \rightarrow F=1$  transition, for a time long enough to excite the ion completely from the ground state to the  $F=1$  state according to the Rabi flopping formula[35]. According to the orthodox interpretation she has to apply a so called “ $\pi$  pulse” pulse of length  $t_p$  and field strength  $E_\pi$  so that

$$(18) \quad E_\pi = (\pi\hbar)/(t_p\varphi)$$

$\varphi$  is the magnetic dipole transition element between the  $F=0$  and  $F=1$  states (the transition is forbidden for electric dipole radiation) which is given in good approximation by the Bohr magneton because the wavefunctions of the two states are quite similar. Let us assume that Silvia1 applies a pulse which is a factor  $\sqrt{2}$  longer to compensate for the fact that Silvia2 does not apply any pulse (“MWI  $\pi$  pulse”).

This whole action will take something like a second at least (for a mechanical “Silvia” it could be performed faster, certainly within a  $\mu\text{sec}$ ). Silvia2 waits for a certain time to allow Silvia1 to apply the microwave field. After this she applies a Laser field to determine the state of the ion. If the MWI interpretation is correct, Silvia2 will find it in a fraction  $p$  of the experiments in the  $F=1$  case prepared by Silvia1. If the inelastic microwave excitation is the only interaction of ion with the environment (i.e. the ion is completely isolated) we get for the damping factor due to excitation according to eq.(16):

$$(19) \quad D_t \simeq \exp(-\sigma_{exc}\phi t)$$

here  $\sigma_{exc}$  is the cross section of the ion for excitation from the  $F=0$  to the  $F=1$  level with resonant microwave radiation.  $t$  is the time period for which the rf field was applied, and  $\phi$  is the flux of the exciting radiation. The excitation probability is given as:

$$(20) \quad p = \sin^2(\nu t)$$

where  $\nu = \varphi E_\pi / (\hbar 2\sqrt{2})$ . For a “MWI  $\pi$  pulse”  $p$  is 1 and  $D_t$  can be easily evaluated as  $1/e$ . Intuitively one can say, that in this situation only one full interaction took place (the absorption of one microwave photon). Complete decoherence needs more than one interaction so  $D_n$  is much larger than zero. Normally Silvia2 will completely decohere the

ion when determining its state with the method described by Itano et al.[34], because the detection of the fluorescence radiation is very inefficient, and many inelastic collisions of 194 nm photons take place for a state determination.

This calculation is only correct in the “one-and-only-one interaction” approximation of Stodolsky[27] in which the different collisions of the ion on other particles are treated as completely independent. It is unavoidable in our situation that there is “feedback”, i.e. a given collision acts on a wavefunction of the ion which is already decohered to some degree by the previous collisions. As a result the excitation of  $|A_2\rangle$  will be less effective and  $p$  will be somewhat smaller than 1. Its exact value depends on the detailed geometry of the experimental setup but is clearly never much smaller than 1, because in the absence of other mechanisms the correlation has its origin in the inelastic scattering of the ion. I find with a numerical calculation that e.g. a “MWI  $\pi$  pulse” applied in world 1 would lead to  $p=0.163$  in the “feedback” case, versus  $p=1.0$  in the “one-and-only-one interaction” approximation. In this calculation I made the simplifying assumption that  $D$  develops strictly according to eq.(16). Itano et al.[34] repeated the cycle “preparation-rf field application-measurement” for hundreds of times in their experiment so also values of  $p$  much smaller than 1 would be measurable.

We have to check if decoherence by other sources can be avoided for at least a few seconds so that the assumption of complete isolation of the ion made in the previous paragraph is justified. These sources are:

- a. scattering of remnant gas atoms in the trap on the ions
- b. elastic scattering of the microwave field on the ion
- c. interaction with the constraining fields holding the ion

Note that only b. is in principle unavoidable, the others could be avoided with a more advanced technology. For contribution a. I get, inserting typical operating parameters of the set up used by Itano et al.[34] into eq.(17):

$$(21) \quad \Delta t_{dec} = 8 \left( \frac{2.4 \cdot 10^{-18} m^2}{\sigma_c} \right) \left( \frac{T}{300 K^\circ} \right) \left( \frac{nbar}{p} \right) sec$$

here  $\sigma_c$  is the elastic cross section; its size (for room temperature) has been taken for  $H_2$ -Hg collisions (at room temperature) from the calculation of Bernstein [36].  $T$  is the temperature, its dependence here does not take into account the change of  $\sigma_c$  with energy (which is however very small around room temperature).  $p$  is the rest-gas pressure. It is possible to achieve vacua much better than a  $nbar$  in ion traps (see e.g. Ref. [37]).

For b. one gets in the same way the decoherence time scale of elastic scattering of a microwave field with a frequency  $\omega$  and an intensity that effects a  $\pi$  pulse in  $t_p$  seconds. For the flux  $\phi$  in eq.(17) I set:

$$(22) \quad \phi = \frac{\epsilon_0 c E_\pi^2}{\hbar \omega}$$

where  $E_\pi$  is the electric field strength of a MWI- $\pi$  pulse(eq.(18). Inserting this relation gives:

$$(23) \quad \Delta t_{dec} \simeq 2.8 \cdot 10^{22} \left( \frac{\varnothing}{\mu_B/c} \right) \left( \frac{t_p}{sec} \right) \left( \frac{5.2 \cdot 10^{-40} m^2}{\sigma} \right) \left( \frac{\omega}{40.5 GHz} \right) sec$$

The cross section is the Thompson cross section which I averaged over scattering angle. The Rayleigh cross section is negligible in our situation.

Case c. is treated in a similar way because it is well known that only time dependent fields can cause decoherence [6]. Even for Penning traps with static fields it is impossible to prevent residual time variability with a fraction  $f_v$  of the total field strength. Without load (as in our case)  $f_v \simeq 10^{-10}$  is achievable for static confining fields  $E_c$  with a strength of about 1000 V/m typical for the traps used by Itano et al. (their ion-trap setup is described in Gilbert et al.[38]). The “worst” case (leading to the shortest decoherence time) is a variability  $\omega$  on a time scale similar to the duration of the experiment. For this case one then obtains:

$$(24) \quad \Delta t_{dec} \simeq 76 \left( \frac{5.2 \cdot 10^{-40} m^2}{\sigma} \right) \left( \frac{\omega}{1 Hz} \right) \left( \frac{1000 V/m}{E_c} \right)^2 f_v^{-2} sec$$

Though it is not of critical importance for our problem, it is easy to show that the decoherence time scale induced by UV Lasers used by Itano et al.[34] via Rayleigh scattering is on a time scale of many years. This surprising ineffectiveness of light to decohere wave functions was already noticed by Joos and Zeh in the connection with chiral eigenstates of molecules [29]. As pointed out in the previous paragraph eqs.(23,24) are expected to underestimate the true decoherence time, because I assumed in their derivation that the wavelength of the particles on which the ion scatters is much smaller than the spatial extension of the ion wavefunction, which does not hold in typical setups.

The reader might object that something has to be wrong with my proposal because it violates energy conservation in a given world (Silvia2 could receive energy from a parallel world). Fundamental principles (like invariance to time translations [39]) require energy conservation only for the whole universe however, and not for single branches which are very special entities singled out by individual humans. Because the energy Silvia2 receives is always lost by Silvia1 there is no violation of energy conservation in the universe. Dicke found some time ago that energy conservation is violated in certain quantum mechanical measurement setups for arbitrarily long times[24]. He holds that this poses no serious problem because the expectation value for the amount of energy violation turns out to be zero (i.e. repeating the measurement many times, energy is lost as often as it is gained). In the conventional interpretation of quantum mechanics there seems to be a problem however, because Dicke’s result means that e.g. the fundamental principle of time translation invariance would be violated on macroscopic time scales. In the MWI Dicke’s situation corresponds to worlds which have a different energy expectation value of the system immediately after they were created due to branching (one is higher and the other lower than the one before

branching[24]). The average of their energy expectation values is the energy expectation value before the branching, and energy conservation holds at all times. This “restoration of conservation laws” in the MWI, which arises when all branches of the quantum state are considered together was already pointed out by Elitzur and Vaidman[40].

## 5 Conclusion

The prediction of the orthodox interpretation [5] is that the ion in our example experiment is never observed in an excited state by Silvia2: the measurement is surely finished after the photon from the polarization filter has not been detected by Silvia2 and thereafter only Silvia2 exists. The “logical” and “many histories” interpretations [12] probably lead to a similar expectation, though it is not completely clear to me what their quantitative prediction would be. Hidden variable models are devised in order to “destroy” Silvia1; their prediction is therefore the same as in the orthodox interpretation by definition. For the MWI it has been shown in the previous sections that inter-world communication on a time scale of minutes should be possible with state of the art quantum-optical equipment. The experimental verification of this possibility would thus rule out the above mentioned alternatives to the MWI.

The limiting factor in extending  $\Delta t_{dec}$  even further (i.e. in “keeping the communication channel open for longer”) seems to be the rest gas in the vacuum of the ion trap at the moment. The fascinating problem of how to optimize the communication in order to transfer large amounts of data (e.g. TV pictures) would be beyond the scope of this paper.

The detection of parallel worlds would finally clarify the fundamentals of nonrelativistic quantum mechanics: nature would have an objective deterministic reality completely independent of human consciousness and fully described by the Schrödinger equation together with the second quantization conditions for the wave field. To communicate with parallel worlds goes of course completely against “common sense”, but it does not lead to any inconsistencies or violations of known physical principles. A similar opinion was voiced by Polchinski[41] who showed that interworld communication is possible within Weinberg’s nonlinear quantum mechanics. The recent speculation of Gell-Mann and Hartle[42] about a possible communication with “goblin worlds” has also certain parallels with the proposal of this paper.

The applications of this effect in physics would be manifold e.g. in the investigation of Chaos or for improving statistics in the study of rare processes. Outside physics inter-world communication would lead to truly mind-boggling possibilities, e.g. in psychological research or for the extension of computing capabilities in computers and humans.

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